External Grant Award Nos. G09AP00115 and G09AP00116

Earthquake Hazard in the Sacramento-San Joaquin River Delta Area: Insight from Seismic Velocity and Attenuation Tomography: Collaborative Research with UW-Madison and UC-Davis

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Abstract

We have capitalized on the collection of new seismic data in the Sacramento-San Joaquin River Delta (SSJRD) area to develop an improved three-dimensional (3D) tomographic model of the P-wave velocity structure of the crust and the first 3D P-wave attenuation model for the SSJRD area. For the velocity tomography work, we are integrating arrival time data from temporary stations deployed in the SSJRD area by our USGS collaborators J. Fletcher and R. Sell into existing datasets used previously for regional-scale seismic tomography studies. The new data available to date provide incremental improvement to the existing 3D seismic velocity models, but confirm the presence of a very strong velocity contrast between the relatively fast rocks of the East Bay area and the rather slow sediments and sedimentary rocks extending to great depth beneath the SSJRD area. The 3D attenuation model is a completely new and fundamental contribution to future wave propagation studies for earthquake hazard estimation in the SSJRD area. Using t* measurements obtained from regionally recorded earthquake spectra, a two-step process was followed to obtain (1) an initial regional-scale 3D model using a simplified parameterization and (2) a finer-scale 3D model focused on the SSJRD area. The results obtained to date support a relatively low Qp for the crust beneath the SSJRD. The area of low Qp extends northwest of San Pablo Bay, whereas there is higher Qp southwest of the SSJRD, implying potentially stronger ground motion for earthquake sources to the southwest of the SSJRD than to the northwest.

Project Results

We report on our development of an improved three-dimensional (3D) tomographic model of the P-wave velocity structure of the crust and the first 3D P-wave attenuation model for the SSJRD area. For the velocity tomography work, we are integrating arrival time data from temporary stations deployed in the SSJRD area by our USGS collaborators, J. Fletcher and R. Sell, into existing datasets used previously for regional-scale seismic tomography studies. The 3D attenuation model is a completely new and fundamental contribution to future wave propagation studies for earthquake hazard estimation in the SSJRD area.

Updated 3D Vp Model

The starting point for our Vp tomography work is the Subregion 2 3D model from the Lin et al. (2010) statewide 3D model. The dataset and inversion grid are depicted in Figure 1. Figure 2 shows the stations that have been deployed by Fletcher and Sells and 15 of the 17 earthquakes with usable data (the other two lie off the map).

The P-wave arrival times at the temporary stations were picked manually from waveforms obtained through the IRIS Data Management Center and combined with network picks for the same earthquakes. The small number of regional earthquakes with adequate signal-to-noise ratio (S/N) recorded so far by the USGS array has limited the improvements possible for the regional 3D velocity model.

The tomographic inversions were carried out using a regional-scale version of the double-difference tomography code tomoDD (Zhang and Thurber, 2003; Zhang and Thurber, 2006). Cross-sections through the updated model are shown in Figure 3. The sharp velocity contrast between the high-Vp rocks of the East Bay and the low-Vp sediments and sedimentary rocks beneath the Delta area are evident in all the sections. Also apparent is the varying shape of the low velocity region beneath the Delta and the sharper velocity contrast at depth in the northwest.

Body-Wave Attenuation Tomography

Tomographic inversions are now commonly applied to determine the 3D attenuation structure in a manner comparable to velocity tomography. Typically, such studies use the high-frequency decay rate of direct-wave amplitude spectra to determine the whole path attenuation, quantified by t* values. The t* values from a suite of earthquakes observed by a network of stations are then inverted for the 3D Q structure, preferably using a 3D velocity model to trace the ray paths along which the t* values are accumulated (Eberhart-Phillips and Chadwick, 2002).

During our current project, we are determining 3D Q of the SSJRD using t* from local and regional earthquakes. The attenuation tomography equation can be written in integral form as

$$t^* = \int_{\text{raypath}} [Q(x,y,z)\ V(x,y,z)]^{-1}\, ds$$

where V is either the Vp or Vs 3D model and ds is an element of path length. Since the velocity structure and earthquake location are known, this integral can easily be discretized and solved.

Similar to our previous studies, the t* values are determined from spectral fitting of data from a short window (~2.5 s) beginning at the P-wave or S-wave arrival (Eberhart-Phillips et al., 2008; Wang et al., 2009). The Q so determined describes the loss along the path as the first arrival travels from the source to the receiver.

The velocity spectrum $A_{ij}(f)$ for event i observed at station j

$$A_{ij}(f) = 2\pi f\Omega_0 * \frac{f_c^{\,2}}{\left(f_c^{\,2} + f^2\right)} * \exp[-\pi f(t*_{ij})]T_j(f)$$

is fit with three parameters: the low-frequency spectral level, Ω_0, corner frequency, f_c, and t*, assuming an f^2 source model. A common event f_c is used for all stations. In previous regional studies, stations with spectral peaks and poor t* fits were simply discarded. For the Delta project, we have developed code to implement site response so that all stations can be included and site effects can be understood. We also note that for our current work we are analyzing P waves to produce a 3D Qp model.

The site response, $T_j(f)$, incorporates local effects that are common to all the earthquakes at a station. First t* values are obtained without site response. Then site response is determined by averaging together all the residuals, using a 5-point moving average, and limiting the effect of high residuals and cases where there are few good S/N observations. An example is shown in Figure 4, where the dashed line is the average, the solid line is the determined site response, and the number of good records at each frequency is labeled along the top axis. Thus consider that WENLBK has many good records and significant site response, while HOL1YU has significant average residuals but too few good records to infer that the average residuals represent the general site response.

An example of the t*-fitting is shown in Figure 5. The thin line shows the spectra without site response, the thick line shows the spectra after removal of site response, and the red line shows the fit theoretical spectra. We are using both permanent and temporary station data to obtain the 3D Qp structure. Clipped records and poor S/N records are discarded, and the t* data are weighted according to a quality based on the S/N and the misfit.

Regional 3D Qp model

Most of the sources are outside of the Delta so we need to have a regional 3D Qp model as an initial model for the detailed Delta inversion. Well-constrained regional 3D velocity models have already been developed (Lin et al., 2010). Thus to simply get the regional 3D Qp initial model, we are solving for Qp as a function of Vp, using a relatively small number of regional events.

In general Qp is not a function of velocity, and it often displays significant variations due to temperature and fluid content even when the velocity is relatively uniform. However, broadly different types of material will also differ in Qp. The extensive sedimentary deposits will have relatively low Qp relative to competent rock, and metamorphosed mafic rock may display relatively high Qp. In the California region, the 700-km long Great Valley is well defined by low Vp in the existing velocity model. Since we have only a small amount of good t* data in the Delta study area, we aim to get an estimate of the Delta sedimentary rock Q by inferring Q of the large Great Valley low Vp area.

In the first stage, a regional-scale t* inversion was set up assuming that Qp is a function of Vp. Qp was parameterized at 10 defined Vp values, with linear interpolation between those values. Throughout the process, seismic rays from the regional earthquakes were traced through the 3D Vp model of California of Lin et al. (2010). Along the raypath, the partial derivatives are accumulated for Qp, based on the Vp at each raypath point. The resulting Qp function is shown in Figure 6. Low Qp (< 200) is found for the low Vp rock (< 5 km/s), and Qp rises to 500-600 for rock with moderate Vp (6-7 km/s). High Qp (> 900) is found for the high velocity uppermost mantle (Vp > 8 km/s), although Qp decreases for higher velocity (> 8.7 km/s) as the mantle becomes warmer and more ductile at greater depth.

This inversion produced a regional 3D Qp model, illustrated for 4-km and 27-km depths in Figure 7. We use 6,492 t* data from 107 earthquakes. This 3D model provides a 29% reduction in data variance from a uniform Qp model. The low Qp Great Valley is apparent in the shallow plot, and in the deeper plot, the high Qp uppermost mantle is apparent, with crustal thickening under the Sierra Nevada Mountains evidenced by a somewhat lower Qp at depth.

Delta area 3D Qp inversion

For the area within about 100-km of the Delta, we carried out a 3D Qp inversion, using the regional 3D Qp model as the initial model. The area is shown as a white box in Figure 7. For simplicity we used the same 10-km grid as the Lin et al. (2010) velocity model. The results are shown in Figure 8. In the upper crust, there is low Qp beneath the SSJRD, extending northwest of San Pablo Bay. In contrast, there is higher Qp southwest of the SSJRD, implying potentially stronger ground motion for earthquake sources to the southwest than to the northwest. Qp is also high in the lower crust, suggesting that sources ~100 km away may still have potential for significant strong ground motion.

The resolution is illustrated by the spread function in Figure 9. The 1-km-depth resolution plot illustrates the distribution of stations. The Delta array stations are individually plotted as triangles, and their density is similar to the 10-km grid giving good spatial resolution at that location. The white areas have no stations and no resolution, so the results there, northeast of the Delta array, come from the regional model. The moderate resolution areas have adequate data sampling but may have smearing across greater than 10-km areas.

The resolution and uncertainty of the 3D model are also shown by comparison to an alternate 3D Q inversion that was done with a uniform initial Qp model. This shows which features come from the regional model. In this alternate inversion (Figure 10), the Sacramento Valley appears to only have low Qp in the location of the dense Delta array. However the low Qp is not low enough and has significant smearing to 20-km depth. This demonstrates the importance using the regional model as the initial model. The simple initial model produced a less reliable 3D Q model, and it did not fit the t* data as well as the inversion with the regional initial model.

The 3D Qp model that we have obtained provides a useful image of the Qp variation, however it is the first step. The Delta array will be expanded and will continue to operate for another year or more, providing additional data and greater spatial coverage. Our subsequent attenuation models will be more detailed and will include Qs in addition to Qp.

Discussion and Conclusions

We have updated a regional 3D P-wave velocity model for the SSJRD area using double-difference tomography and developed new regional and local P-wave attenuation models encompassing the SSJRD area. The 3D Vp model is little changed due to the limited amount of new data available to date, but it confirms the presence of a sharp velocity contrast between the high-Vp rocks of the East Bay and the low-Vp sediments and sedimentary rocks beneath the Delta. The 3D attenuation model is a completely new and fundamental contribution to future wave propagation studies for earthquake hazard estimation in the SSJRD area. Spectral fits for about 6500 P waveforms were used to obtain t* values which in turn were used for the Qp modeling. We used a progressive approach to the attenuation inversion, first determining a regional-scale Qp model parametrically linked to the regional Vp model and then using that result as an initial model for a 3D tomographic inversion. In the upper crust, there is low Qp beneath the SSJRD, extending northwest of San Pablo Bay. In contrast, there is higher Qp southwest of the SSJRD, implying potentially stronger ground motion for earthquake sources to the southwest than to the northwest. Qp is also high in the lower crust, suggesting that sources ~100 km away may still have potential for significant strong ground motion.

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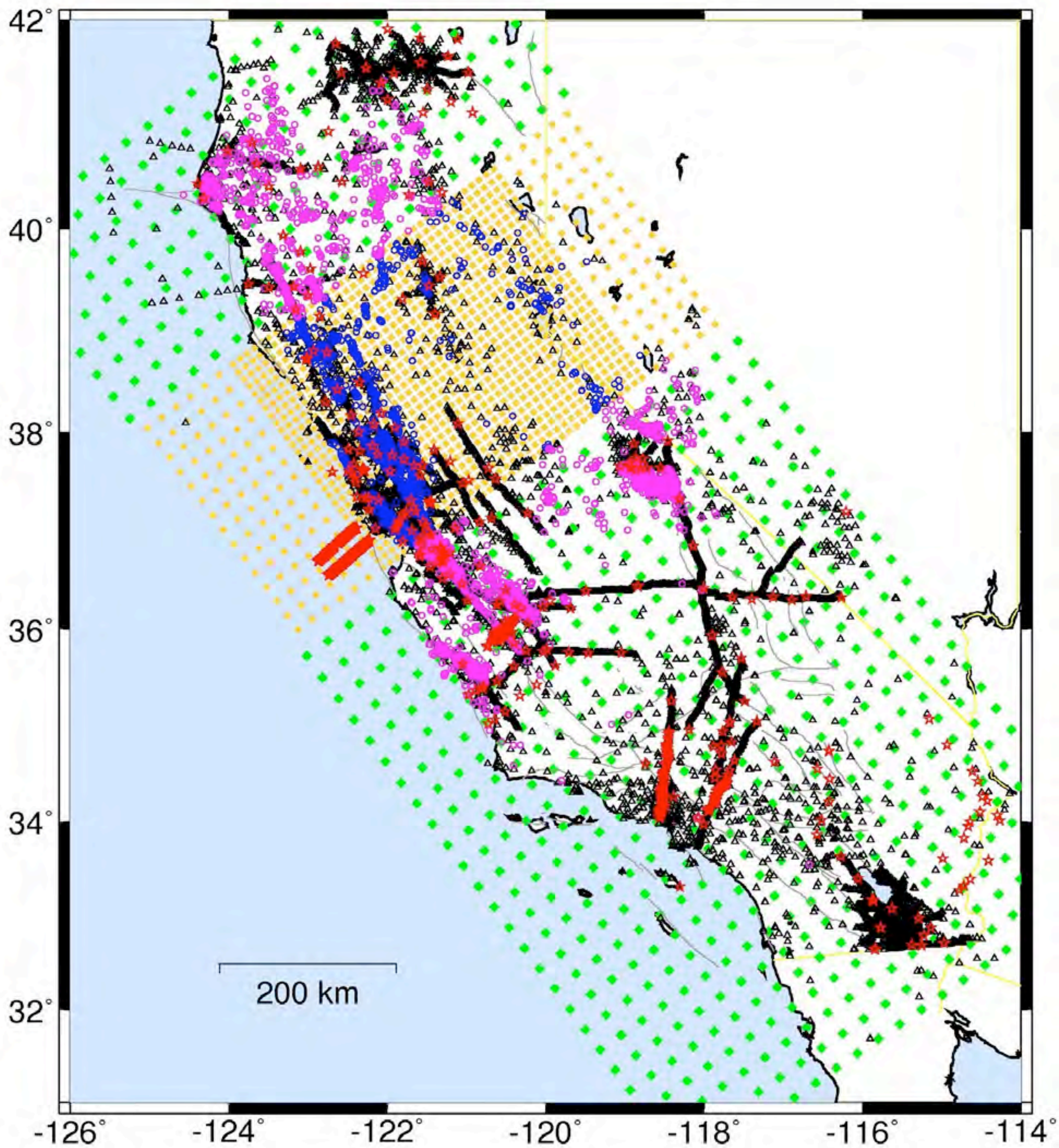

Figure 1. Map showing the full dataset for "Subregion 2" of Lin et al. (2010). This dataset is being augmented by new data collected during the deployment of the temporary stations in the SSJRD area (Figure 2).

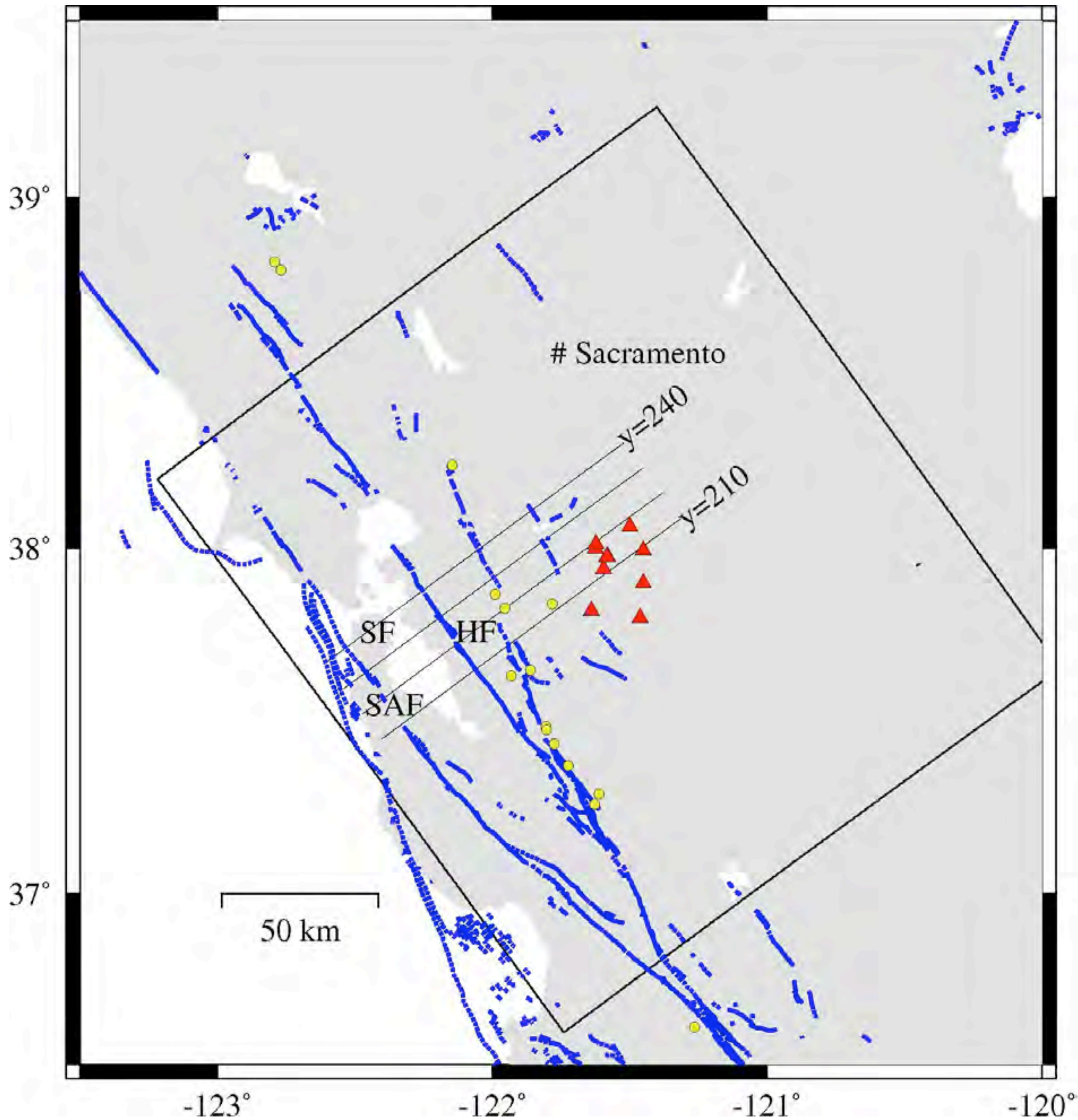

Figure 2. Map showing the USGS stations in and around the SSJRD area (red triangles), 15 of the 17 new earthquakes usable for our tomography work that were recorded by the USGS array (yellow circles), the model area for Qp tomography (box) and main fault traces (blue lines). The four lines oriented NE-SW correspond to the Vp model sections shown in Figure 3.

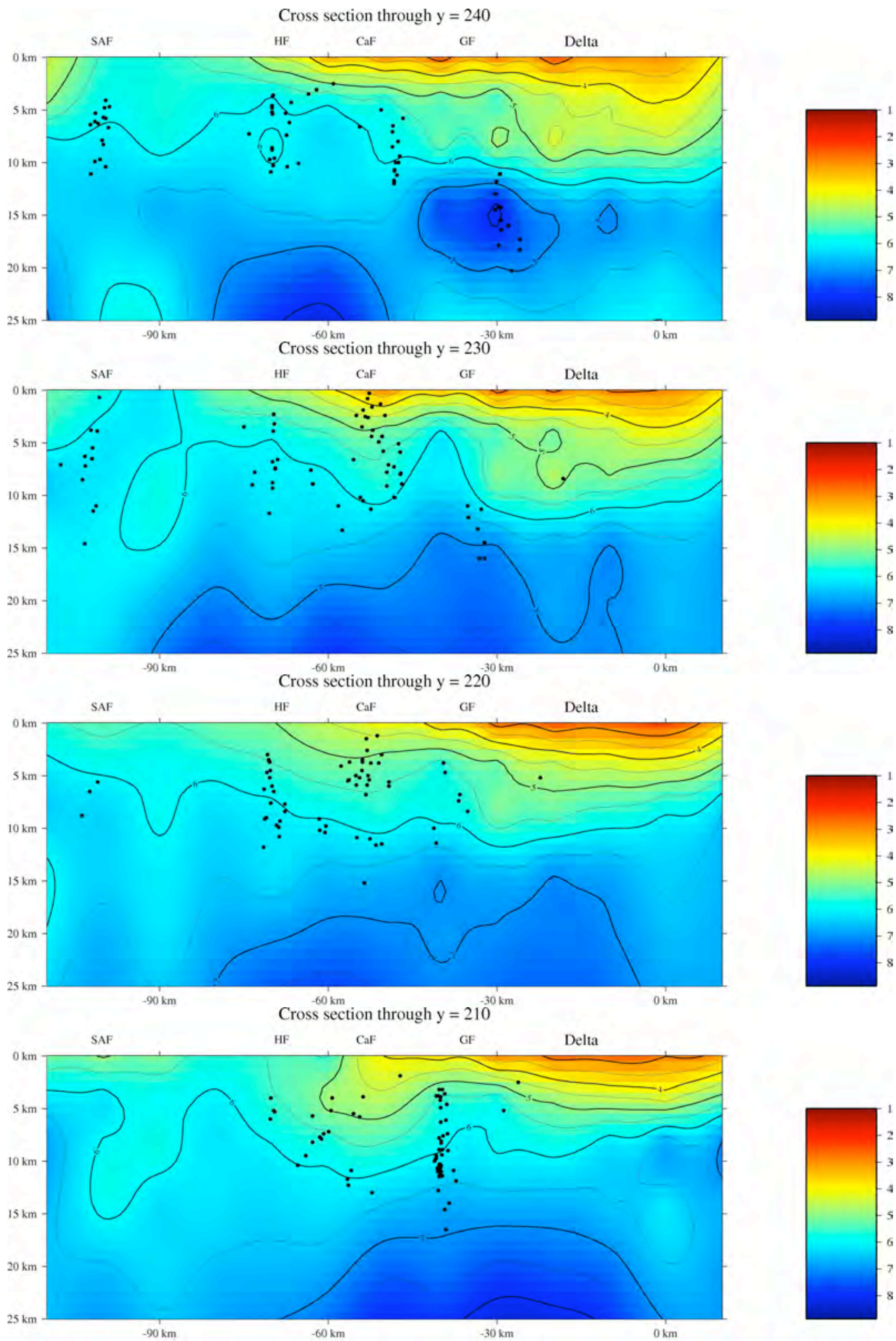

Figure 3. Southwest-northeast oriented cross-sections through the updated 3D Vp model on the section lines and including the data from the new events shown in Figure 2, arranged top to bottom from northwest to southeast. Note the varying shape of the low velocity region beneath the Delta and the sharper velocity contrast in the northwest (sections at y = 240 and 230 km).

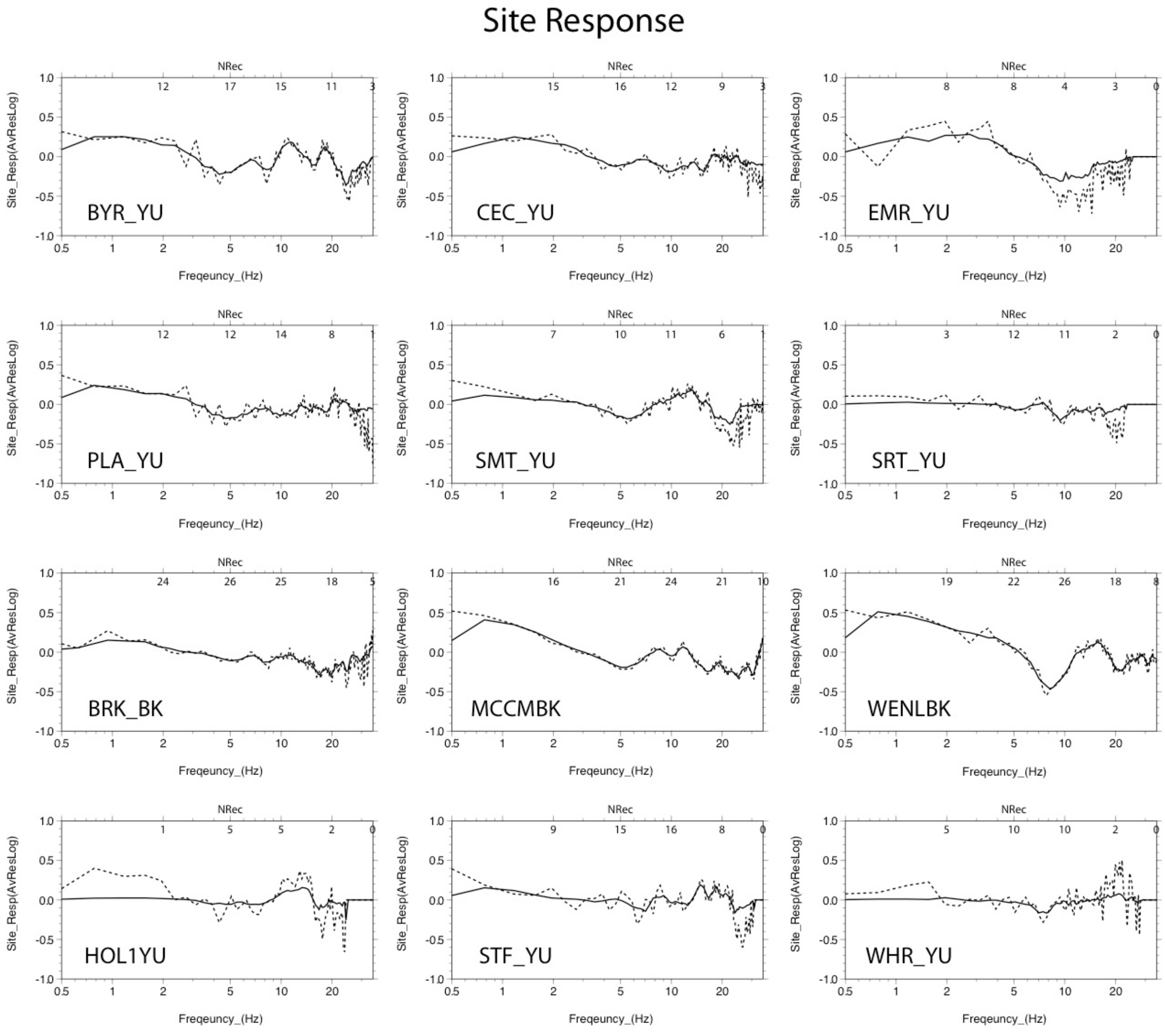

Figure 4. Example of site response determined by averaging together all the residuals, using a 5-point moving average, and limiting the effect of high residuals and cases where there are few good signal-to-noise ratio observations.

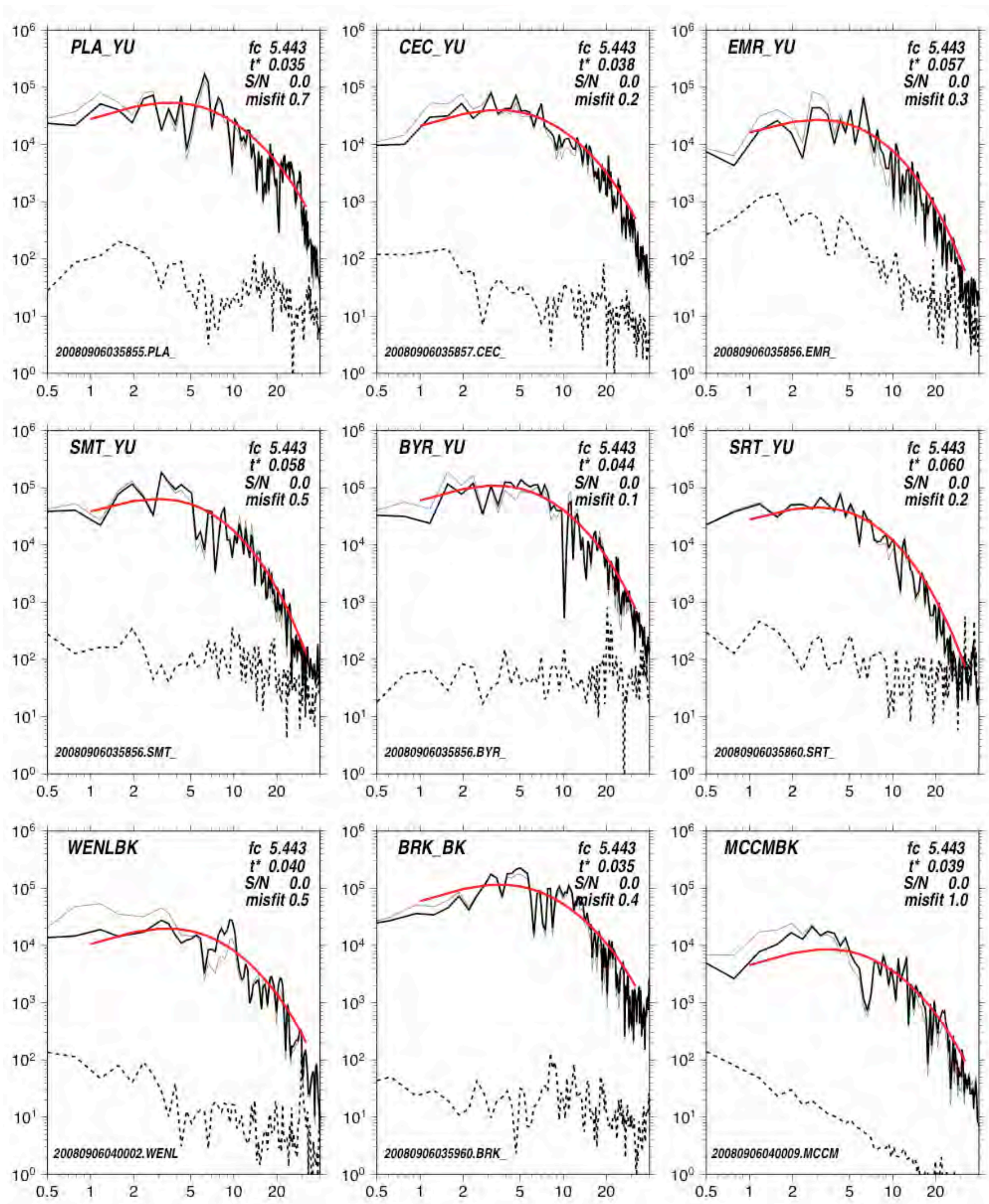

Figure 5. An example of the t*-fitting results. Vertical axes are spectral amplitudes and horizontal axes are frequencies. The thin lines show the spectra without site response, the thick lines show the spectra after removal of site response, and the red lines show the fit theoretical spectra. The dashed lines show the pre-event noise spectra.

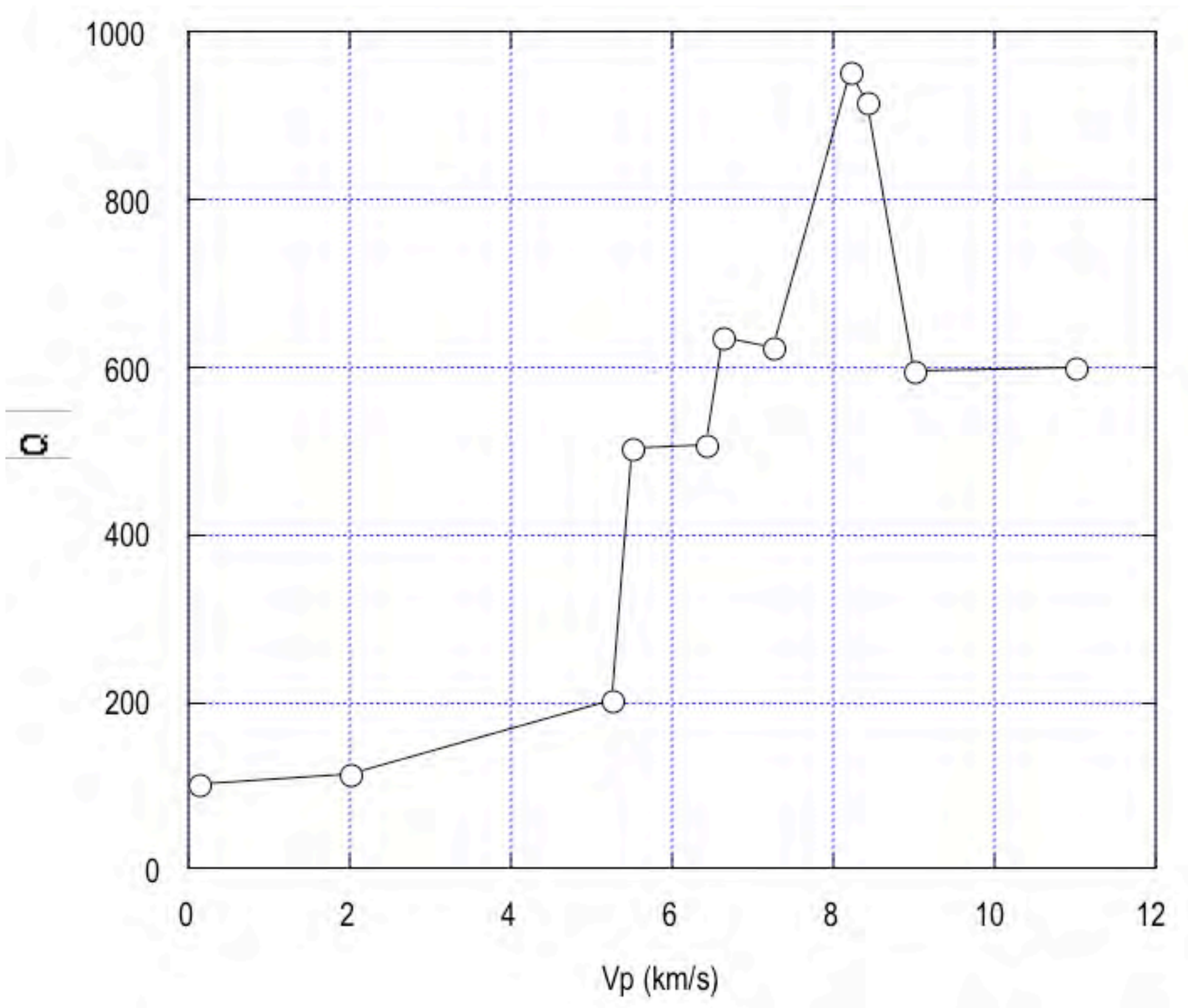

Figure 6. Qp as a function of Vp derived from the regional inversion.

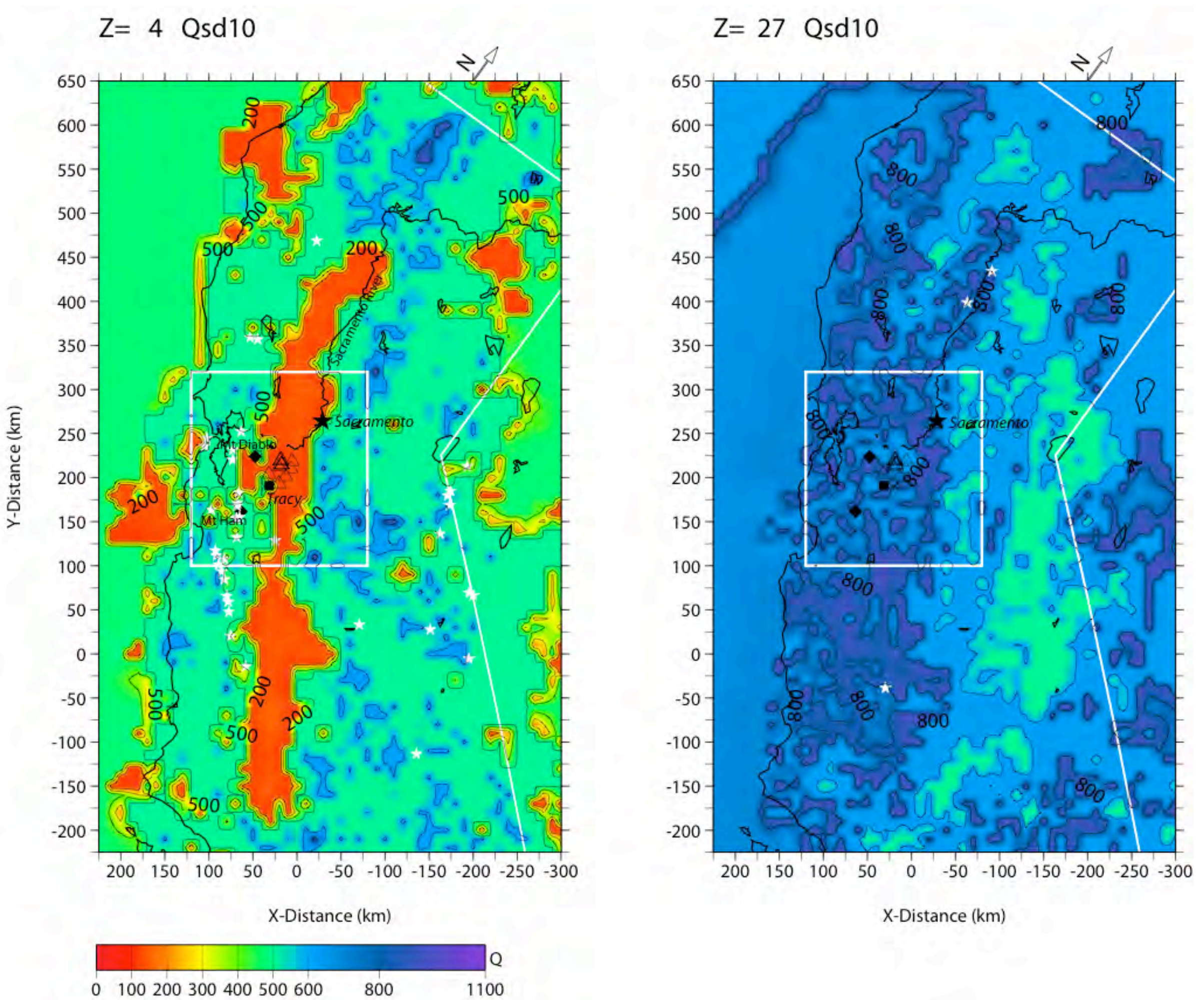

Figure 7. Regional 3D Qp model, illustrated for 4-km and 27-km depth, derived using the Vp-Qp relationship of Figure 6 and the Lin et al. (2010) 3D Vp model.

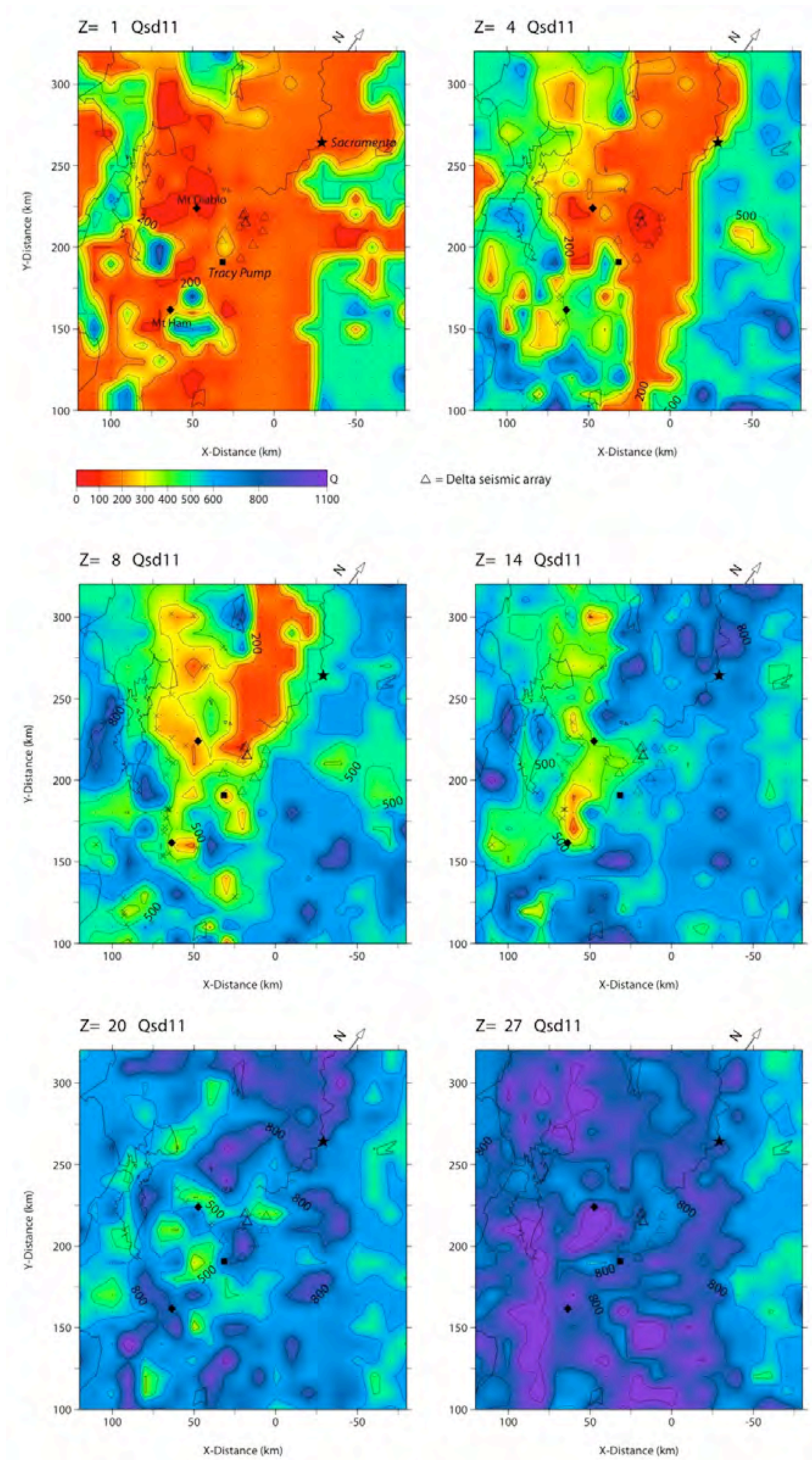

Figure 8. Results of the 3D Qp tomographic inversion for the area shown as a white box in Figure 7, using the regional 3D Q model of Figure 7 as the initial model.

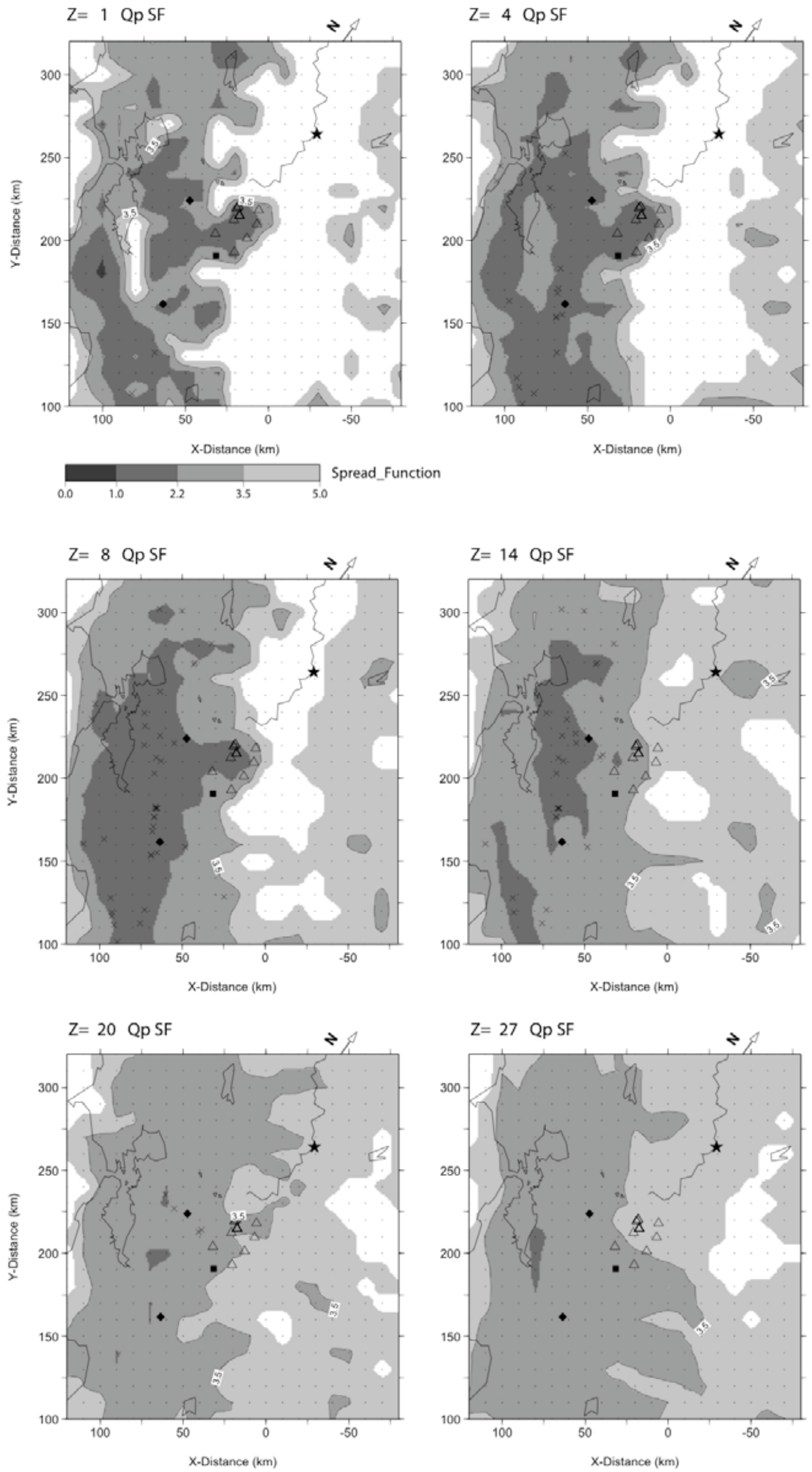

Figure 9. Resolution of the 3D Qp model as indicated by the spread function values.

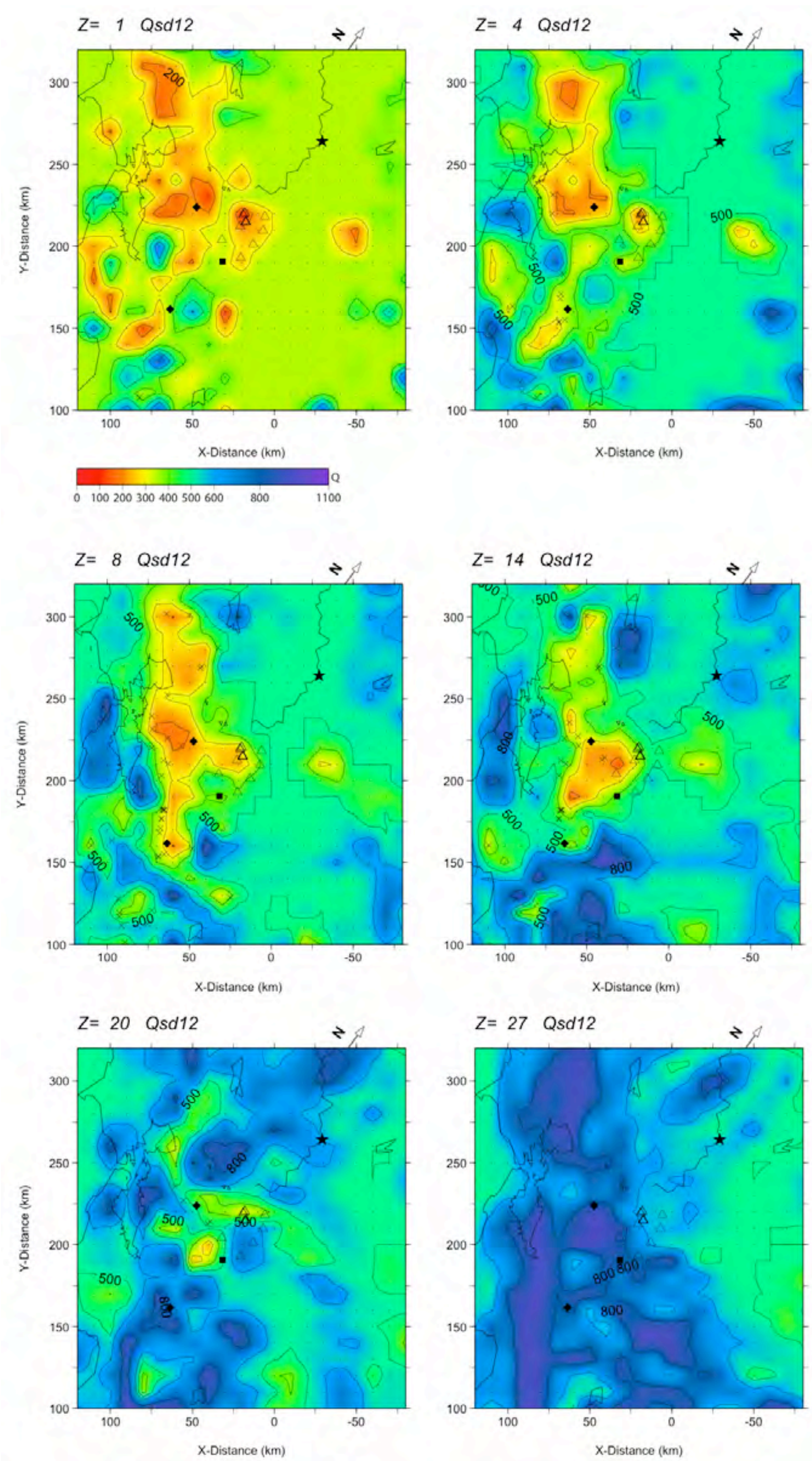

Figure 10. Results of alternate Qp inversion using a uniform Qp starting model.

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